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PRINCIPAL INVESTIGATOR: Lee W. Cross, Ph.D.

CONTRACTING ORGANIZATION: Imaging Systems Technology, Inc.
Toledo, OH 43615-3902

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Lee W. Cross

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Imaging Systems Technology, Inc.
IST
4750 West Bancroft Street
Toledo, OH 43615-3902

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14. ABSTRACT
Under the Phase I Option of the awarded SBIR contract, Imaging Systems Technology (IST) investigated the efficacy of short range, medium data rate non-line-of-sight (NLOS) optical communication using ultraviolet (UV) light in the solar blind region (200–280 nm). The application is wireless transfer of medical data for battlefield combat casualty care. IST improved components of the Phase I test bench hardware in order to experimentally demonstrate feasibility of medium-rate NLOS data communication up to 50 m. To this end, effort was directed towards increasing optical output power. The output power of IST's proprietary UVC-emitting Plasma-shells was increased from 36 μW at the end of Phase I to 70 μW per device at the end of the Phase I Option. An improved pulsed LED emitter source was constructed that increased pulse power from 2.6 mW in Phase I to 124 mW with 12° beam width. The improved LED light source was evaluated outdoors using the test bench system at a range of 50 m, and received photon counts were consistent with medium data rate communication. Future Phase II efforts will develop theory and prototype hardware to achieve the full set of performance goals outlined in the solicitation topic, eliminating the need for wires in battlefield casualty care and many other military applications.

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Introduction

This project investigates the efficacy of short range, medium data rate non-line-of-sight (NLOS) optical communication using ultraviolet (UV) light in the solar blind region (200–280 nm). The application is wireless transfer of medical data for battlefield combat casualty care. Under the Phase I Option of the awarded SBIR contract, Imaging Systems Technology (IST) improved components of the Phase I test bench hardware in order to experimentally demonstrate feasibility of medium-rate NLOS data communication up to 50 m. To this end, effort was directed towards increasing optical output power. The output power of IST's proprietary UVC-emitting Plasma-shells was increased from 36 μW at the end of Phase I to 70 μW per device at the end of the Phase I Option. An improved pulsed LED emitter source was constructed that increased pulse power from 2.6 mW in Phase I to 124 mW with 12° beam width. The improved LED light source was evaluated outdoors using the test bench system at a range of 50 m, and received photon counts were consistent with medium data rate communication. Future Phase II efforts will develop theory and prototype hardware to achieve the full set of performance goals outlined in the solicitation topic, eliminating the need for wires in battlefield casualty care and many other military applications.

Body

Technical Overview

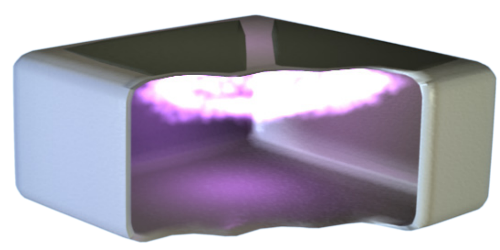

Figure 1. Plasma-shell cutaway showing internal plasma across top electrodes.

This research effort is pursuing two complementary UVC emitter technologies: LEDs and Plasma-shells. A Plasma-shell consists of a hollow, impervious dielectric shell of any shape that encapsulates a pressurized gas that can be ionized into plasma, as shown in Figure 1. UV phosphor in the shell produces tailored emission, and the resulting UVC spectrum is shown in Figure 2 along with the UV LED from Crystal IS used in this work. IST's proprietary manufacturing process is *extremely low cost*; Plasma-shells cost as little as $0.02 each, and can be made from a wide variety of glass, ceramic, or metallic materials. Finished sizes range from 0.5 to 10 mm, and may be filled with a variety of gases with controlled pressures from 5 to 500 Torr. Ceramic shells operate over extreme temperature ranges far greater than LEDs, and are rugged and light-weight (71 mg each).

Plasma-shells are capable of producing UVC emissions at shorter wavelengths than state-of-the-art compact solid-state emitters.

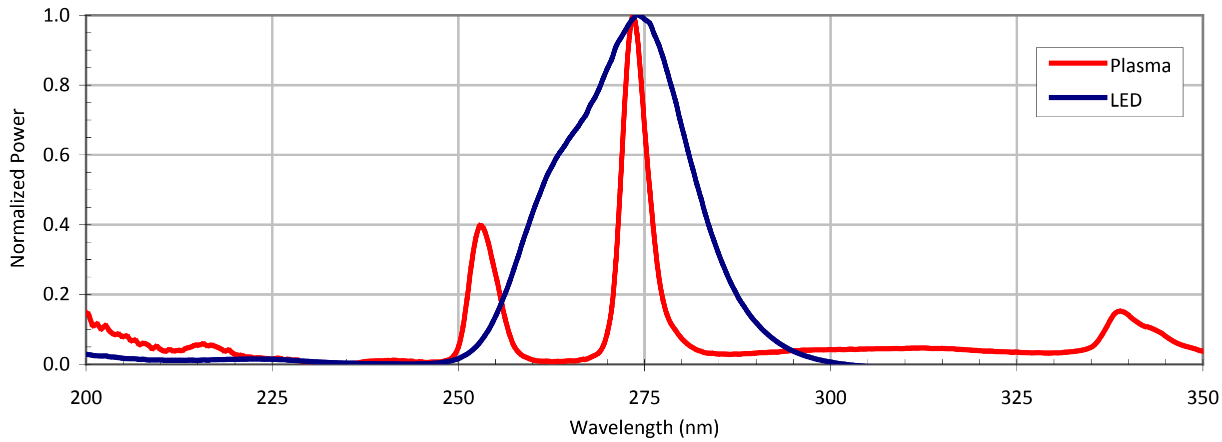

Figure 2. Normalized UVC emission spectra of a Plasma-shell with peaks at 216, 253, and 273 nm, and Crystal IS 273 nm UV LED.

This research seeks to demonstrate the concept of UV NLOS communication envisioned in Figure 3, where large-area flat-panel Plasma-shell arrays communicate with compact transceivers integrated into

(a) (b)

Figure 3. Concept (a) Plasma-shell large-area transceiver and (b) medic PDA with NLOS communication.

medic PDAs and patient vital sign monitors. To support this objective, the following task list was continued into the Phase I Option. Tasks 1, 2, 5, and 6 concluded in Phase I and the highlighted tasks continued in the Phase I Option:

1. Survey literature and industry state of the art (Done)
2. Model NLOS communication channel (Done)
3. **Improve UVC Plasma-shell (Continued in Phase I Option)**
4. **Investigate plasma drive waveform (Continued in Phase I Option)**
5. Build breadboard system (Done)
6. Test breadboard system (Done)
7. **Improve breadboard performance (Continued in Phase I Option)**

The purpose of the remaining tasks is to improve the test bench capabilities in order to demonstrate communication over longer distances. This is accomplished in two ways: increasing emitter power and improving test bench components to increase photon reception and data collection abilities. The objective of Tasks 3 is to increase Plasma-shell emitted power at the component level by optimizing materials and manufacturing processes. Emitted power is also increased by Task 4 where the objective is to develop Plasma-shell drive hardware that produces drive waveforms capable of higher emission, higher efficiency, and medium data rate communication. Finally, the objective of Task 7 is to refine each component in the breadboard system to improve performance and data collection. The results of these tasks are summarized below.

Task 3: Plasma-shell Improvement

Plasma-shell UVC emission was *increased by a factor of 1.9X* in the Phase I Option, from 36 μW per device to 70 μW[1]. This was accomplished by successfully fabricating larger shells with greater emitting surface area; from 4 mm × 4 mm × 2 mm (L × W × H) in Phase I to 9 mm × 4 mm × 2 mm. While this does not directly increase brightness per unit area, larger shells have several benefits. First, for fixed spacing between shells, larger shells will achieve higher fill factors. Second, larger shell dimensions allow longer discharge lengths that directly increase light emission and efficiency. Finally, system cost and reliability improve with less components.

Several other avenues were pursued to increase emission. Higher shell transmissivity can significantly increase light emission. Multiple materials were processed including glass powders from Ceradyne Viox and Schott AG, magnesium aluminate spinel, silicon dioxide, and additives to alumina. No trials produced improvement over current alumina shells, however work will continue in Phase II in order to achieve higher transmissivity that can increase emission by a factor of 6X. Process optimization can also improve power output, and limited optimization trials were attempted in this work. Large shell geometries did not work well with certain process combinations of phosphor loading and shell thickness. Optimization will continue in Phase II to achieve better results.

A test fixture was built to measure internal plasma emission through a thin UV-transparent window. To construct the fixture shown in Figure 4, the top side of a UVC Plasma-shell was removed and the shell was sealed to a fused silica ball lens that is transparent below 200 nm, and was sealed to a gas tube

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[1] Power measured from 250 to 280 nm. Gas mixture of 20% xenon balance neon at 222 Torr. Alumina shell with UV phosphor 10% by weight.

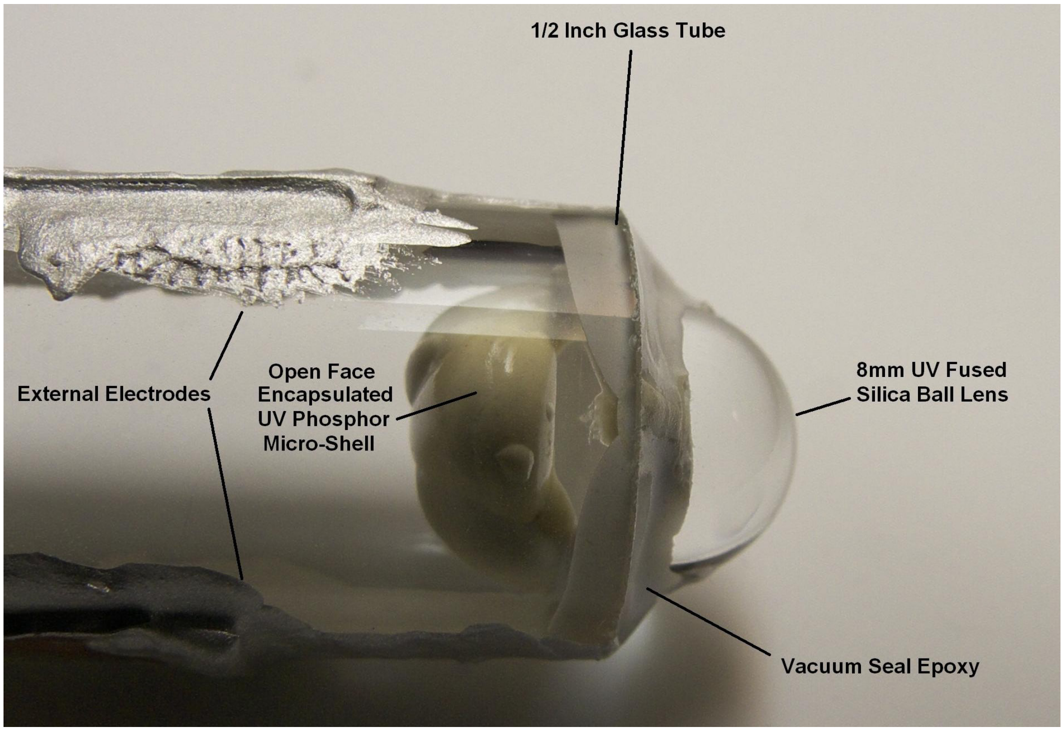

Figure 4. Plasma-shell gas tester fixture with UV-transparent ball lens, used to measure UVC emission various gas mixtures and pressures.

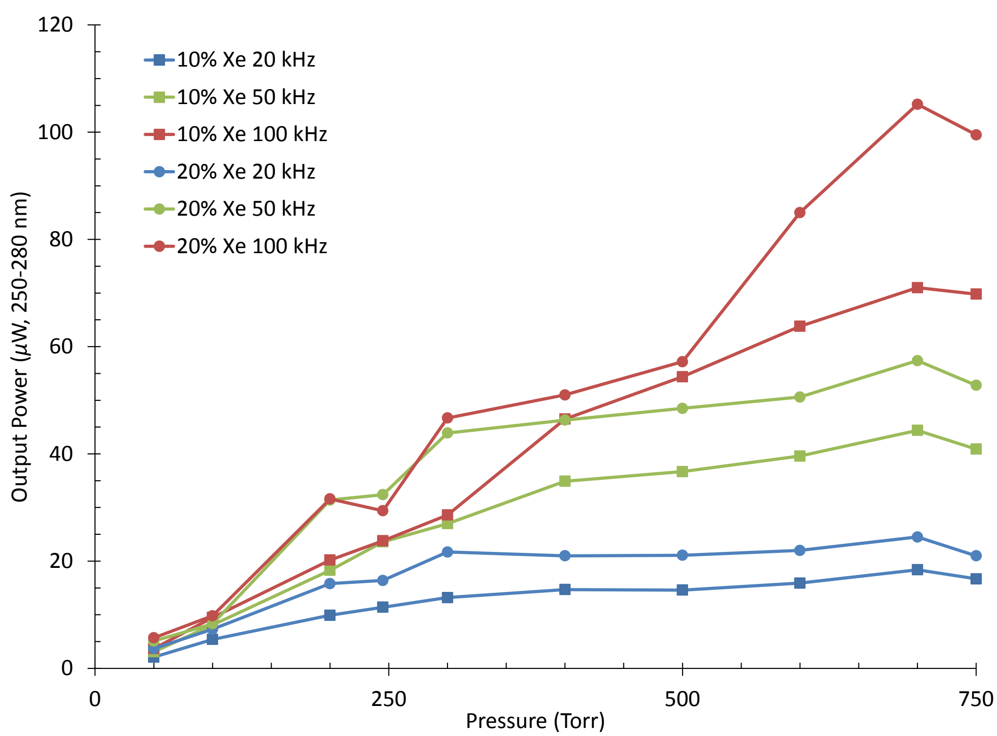

Figure 5. Measured UVC emission of fixture across gas mixture, pressure, and sustain frequency. Higher xenon content, gas pressure, and sustain frequency increase UVC emission.

connected to a high-purity gas fixture. The gas composition and pressure can be independently adjusted, allowing light emission to be tested across a wide variety of gas and waveform parameters. Test results are shown in Figure 5 for measurements of 10% and 20% xenon balance neon gas mixtures sustained at three different frequencies.

There are three important conclusions from this data. First, the use of 20% xenon gas increases UVC emission by 40% on average. Drive voltage is increased by 15% and this is acceptable for our test system hardware. Second, increasing gas pressure from 245 Torr to 700 Torr increases UVC emission by a factor of 2.3X. This is a current process limitation that will be investigated. Finally, the emission peak at 216 nm seen in Figure 6 contains significant energy and could be used in systems requiring shorter wavelengths. This peak is significantly shorter wavelength than UV LEDs are capable of producing. High transmissivity shell material is required in order for that wavelength to escape the shell. In conclusion, the fixture is a useful tool for quickly investigating Plasma-shell UVC emission for process parameters outside of IST's current process capability.

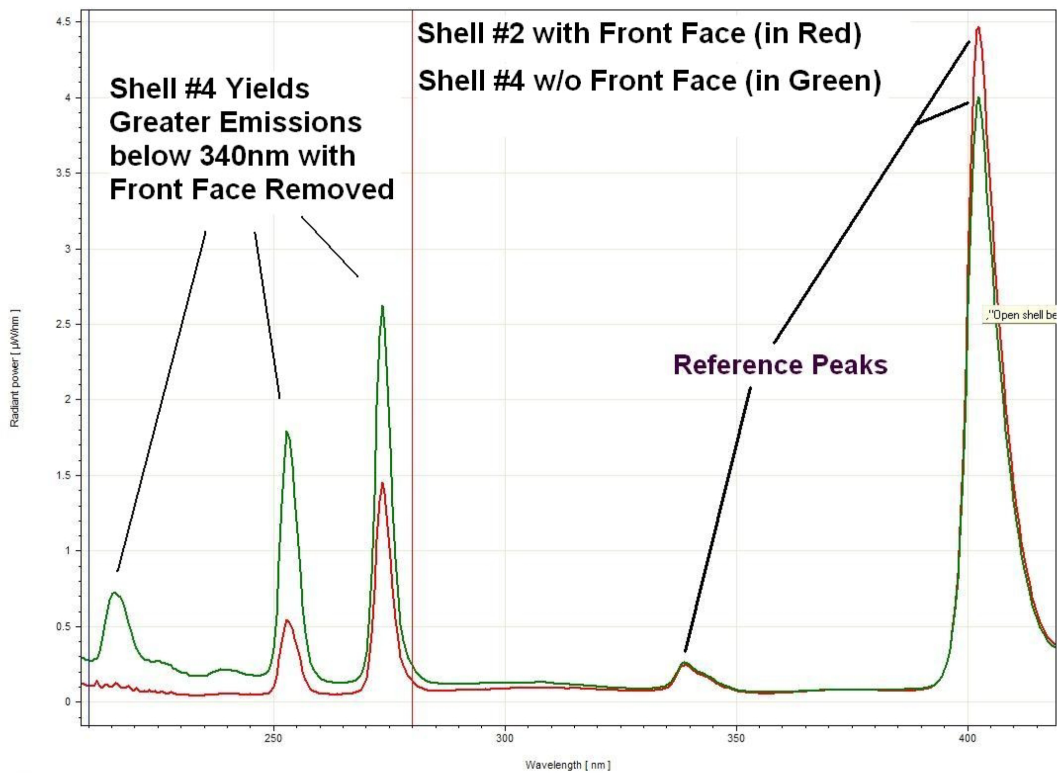

Figure 6. Plasma-shell emission through transparent ball lens (green trace) and alumina face (red trace), in which higher UVC emission is evident with the transparent face. Much higher emission is possible with improved shell transmissivity, especially at shorter wavelengths. UVC emission peaks are seen at 216, 254, and 274 nm.

Task 4: Drive Waveform

A novel three-electrode Plasma-shell drive scheme was designed and implemented in hardware, and basic proof-of-principle tests indicate that this scheme will provide the following benefits: higher UVC emission per component, higher drive efficiency, high-speed addressability of the entire Plasma-shell array, and scalable array power emission. This directly supports performance objectives of longer communication range and reduced power consumption.

Completed Phase I Option work includes simple proof-of-principle tests, design of panel drive electronics shown in Figure 7, electroding of a small number of shells according to the three-electrode pattern shown in Figure 8, and optimization of sustainer circuit energy recovery to increase system drive efficiency. The three-electrode scheme will be tested at the start of Phase II.

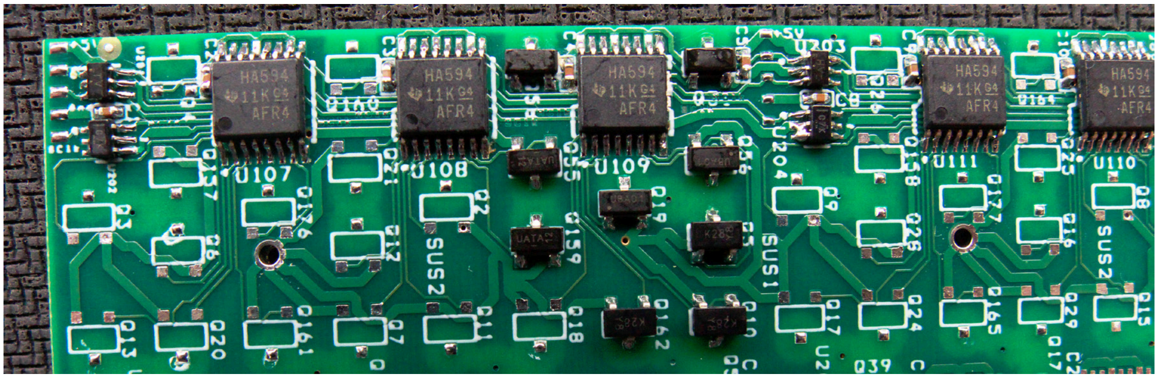

Figure 7. Three-electrode drive electronics partially populated on test PCB. Plasma-shells are mounted on the opposite side.

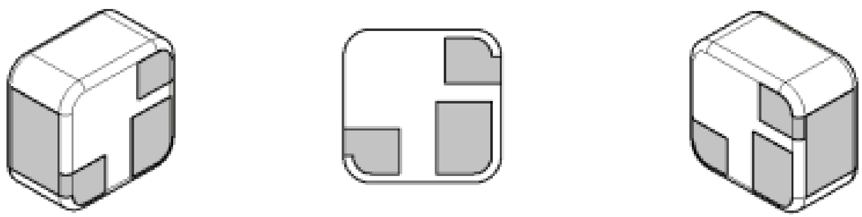

Figure 8. Plasma-shell three electrode pattern. Geometry is shown for 4 mm × 4 mm × 2 mm shells.

Task 7: Improve Breadboard Performance

Most of the test bench components were improved in the Phase I Option in order to demonstrate operation at longer range. Figure 9 shows the breadboard system block diagram that generates 20 μs optical pulses (consistent with 50 kbps data rate) using a pulsed LED source (the Plasma-shell emitter was not tested in Phase I Option), and receives scattered photons with a photon-counting PMT and data-logs the received photon-count-versus-time output onto a laptop computer for later analysis.

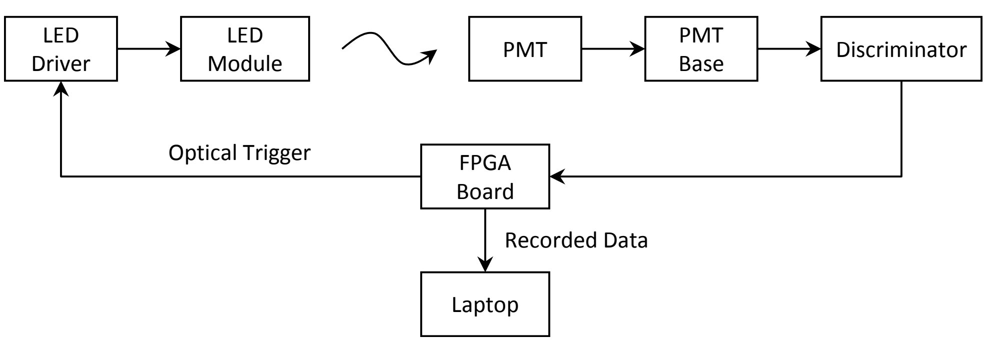

Figure 9. Breadboard system block diagram.

The following test bench components were improved in the Phase I Option:

- The LED driver pulse current was increased from 100 mA to 1000 mA. This resulted in an increase of 8.8X more power per pulse. The pulse rate was set to 100 Hz for this testing to avoid the effect of die heating. Emitted power is expected to decrease significantly as thermal loading increases.
- A better LED from Crystal IS was used. The new LED produced 14.1 mW of optical power at 270 nm, which is an increase of 5.4X over the LED used in Phase I testing and is due to process improvements accomplished by Crystal IS over the last year.
- The LED light source was collimated to a beam diameter of 12° full width half maximum (FWHM) versus the original Lambertian distribution (120°) of an uncollimated LED. The collection efficiency of the lens is only 53%, so significant light is lost, however, despite this loss a narrow beam demonstrated lower path loss during testing.
- Another Hamamatsu R7154 PMT was ordered with lower dark current. Optimal PMT and discriminator voltage set points were determined to be 1000 V and 150 mV, respectively.
- The FPGA Board captures larger sample sizes ($N > 1000$) and logs data to the attached laptop computer.

The system was operated at short range in order to test the multi-sample data logging functionality. Figure 10 confirms a basic characteristic of NLOS photon counting systems: the number of received photons per bit time follows the Poisson distribution. The Poisson distribution and measured photon counts per bit time shown in Figure 10 are in agreement.

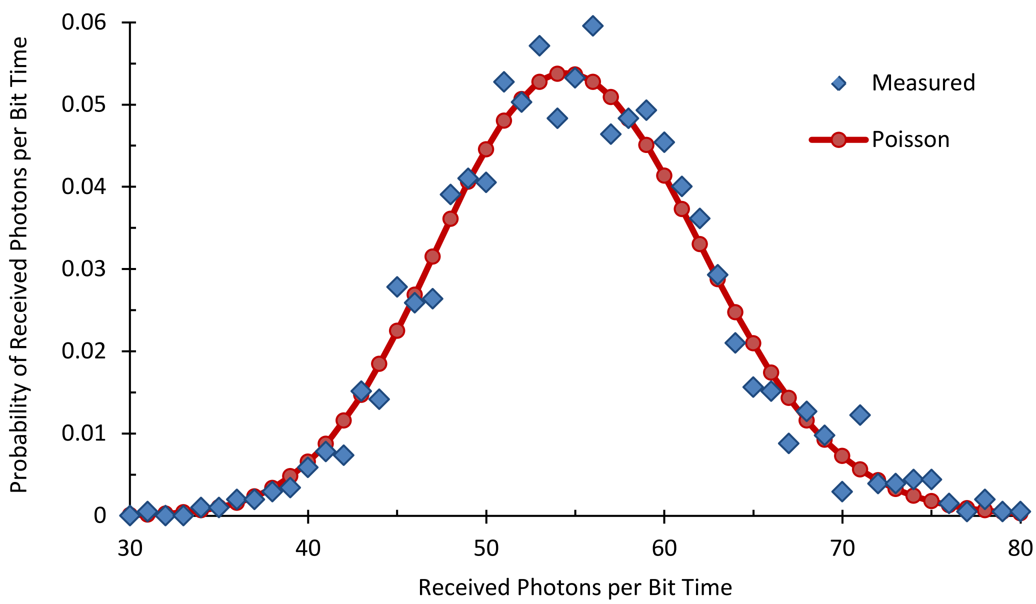

Figure 10. Test bench measured received photon count probability (N = 2048 samples) matches Poisson distribution with mean of 55 µs. This confirms Poisson arrival statistics in the test bench system.

The test bench system was field-tested at a remote outdoor location. All electronics were battery operated and mounted on tripods for easy transportation and field alignment. Because IST has not yet procured a solar blind filter, testing required low ambient level levels that are only possible at night at locations suitable for astronomical viewing. The selected test site is located far from city lights, sixty miles from IST's facility in Toledo. Without a solar blind filter, the average received photon count from the night sky was 0.78 counts per bit time (20 μs). This value would be far lower even in direct sunlight with a proper filter. The sky was clear and no moonlight was visible during testing. There was light fog and high pollen count (9 grains per m^3), and relative humidity was nearly 100%. The test was only completed for one distance because water condensed on the instruments and caused erratic operation immediately after measurements were complete at the first distance. The receiver was pointed at an optimal elevation angle (ϕ) of 45°. Two LED sources were tested at three elevation angles (ϕ = 10°, 30°, and 90° [directly up]); an uncollimated LED with Lambertian distribution (θ = 120°) and a collimated source (θ = 12°). Both LEDs have identical power (listed above). The direct line of sight was blocked at both the emitter and receiver with black felt cards.

Figure 11 shows measured results at 50 m, the maximum distance specified in the solicitation topic. The average received photons per bit time was a minimum of ~5 when emitters were pointed straight up and an order of magnitude greater when collimated and pointed slightly over the receiver. Two conclusions can be drawn from this: first, the received photon count of 55 photons per bit time is more than sufficient for medium data rate communication. With additional processing, this test bench could establish a one-way data link. Second, path loss is an order of magnitude lower when the emitter can be aimed. Pointed, collimated emitters allow lower transmit power and more covert communication.

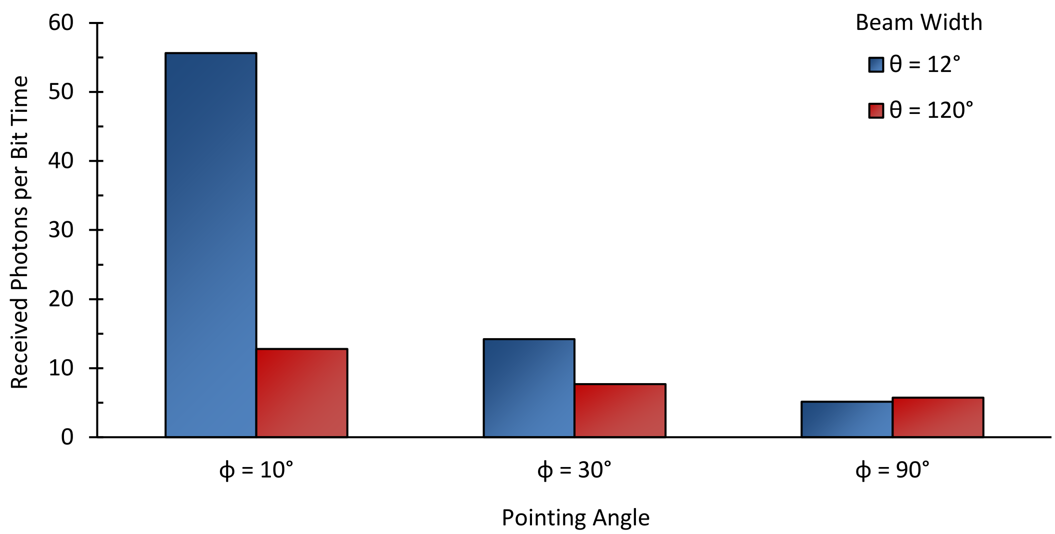

Figure 11. Received photon count for pointing angle (ϕ) and beam width (θ) at 50 m. Narrow beam width significantly improves photon reception at long range for low pointing angles.

Ongoing Plasma-shell Aging Data

Emitter lifetime is a key concern for UVC systems. Aging data is being recorded from Plasma-shells manufactured at the start of Phase I. Figure 12 shows the power output of three UVC shells normalized to burn-in time of 24 hours. Power at 7500 hours is slightly lower than initial power at 24 hours. This demonstrates that Plasma-shells have superior lifetime compared to UVC LEDs with lifetimes as short as 1000 hours.

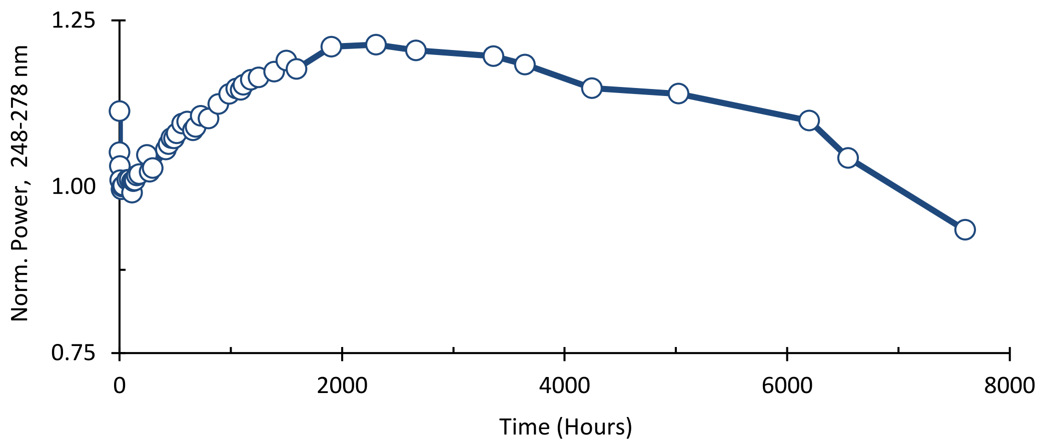

Figure 12. Plasma-shell output power (normalized to 24 hours) is slightly below initial output after 7500 hours of operation.

Outreach Activities

IST is engaging with companies and government organizations that have an interest in the success of this technology. Companies include Robotics Research, LLC, Think-a-Move, Ltd., and Engility Corp. IST has contacted Zephyr Technology Corp., the maker of the Zephyr Bioharness, to assess the suitability of incorporating the Bioharness into an IST hardware test bench that will be used in Phase II. In addition, IST is planning to observe C4ISR medical exercises at Fort Dix in July as an opportunity to observe field-use scenarios and interview medical planners and field medical personnel to better understand application requirements.

IST attended the SPIE Defense Security & Sensing conference on April 30–May 2 in Baltimore to identify state-of-the-art UVC optical and electro-optic components. Many contacts were made with component manufacturers and industry experts, and follow-up work will focus on obtaining UVC solar blind filters and application support for UVC photon counting sensors.

Key Research Accomplishments

- Increased output power by factor of *1.9X*, to 70 μW per device
- Increased UVC pulse power from 2.6 mW to 124 mW
- Demonstrated suitable photon reception at 50 m for medium data rate communication
- Demonstrated Plasma-shell lifetime exceeding 7500 hours (and counting)

Reportable Outcomes

- Awarded ***Phase I SBIR*** for NSF topic EI/ED1 (Electronics, Information and Communication Technologies: Optoelectronic Devices), "UV Plasma-Shell Device for Novel Photocatalytic Process," award # IIP-1248617. Contract started December 2012.
    - Proposes UVA and UVC Plasma-shells (developed in this work) for use in water purification
- Awarded ***Phase I SBIR*** for EPA topic "Efficient Water Purification Using TiO_2 and Novel Activation Method," award # EPD13032. Contract started May 2013.
    - Proposes UVA Plasma-shells for use in water purification and microbial deactivation, with outer layer of titanium dioxide (TiO_2) photocatalyst (ongoing Plasma-shell materials research for larger shells and higher transmissivity).

Conclusion

Plasma-shells provide pulsed UVC emission suitable for UV NLOS communication. They are currently available in large quantities at very low price to enable conformal, low-profile transmitter panels that do not require aiming. In this effort, IST demonstrated Plasma-shell power improvement by a factor of 1.9X to 70 μW per device. This enables high-power panels that operate at extreme temperature ranges at an order-of-magnitude lower price. Life testing out to 7500 hours shows only minor power drop, implying excellent life.

IST improved components of the Phase I test bench hardware in order to experimentally demonstrate feasibility of medium-rate NLOS data communication up to 50 m. Optical power of a single-LED source was increased to 124 mW per pulse with 12° beam width. The LED source was evaluated in the test bench system outdoors at a range of 50 m, and received photon counts were consistent with medium data rate communication. Future Phase II efforts will develop theory and prototype hardware to achieve the full set of performance goals outlined in the solicitation topic, eliminating the need for wires in battlefield casualty care and many other military applications.